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Micro Wind Turbine Viability at the University of Vermont

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Abstract

Wind can be a helpful tool to reduce reliance on non-renewable forms of energy production, such as coal or other fossil fuels. With the use of wind turbines, this energy can be harvested and turned into electricity. Excluding each individual turbine's efficiency, the two most important factors for power production are the sweep area of the blades and wind speed. Often times, sweep area can be maximized in more remote locations, such as a desert, as size is not as much of a constraint. This benefit comes at the cost of more difficult maintenance and energy loss due to transmission losses such as wire resistance. As an alternative that might be available to users in urban areas, I explored the potential feasibility of locally installing smaller wind turbines on the University of Vermont campus. This model would reduce resistance energy losses, installation/maintenance costs, and would utilize otherwise wasted wind energy already available on campus. To explore the viability of such an installation, wind speeds would need to be recorded using an anemometer. Through using NRG #40C Anemometer, along with a data logger, I measured the wind speed over a two-week period from a location on the top of Votey Hall. While realistically a full year of data is needed to make accurate prediction, the small subset acquired can act as a guide for further research in a more in-depth study. Making general assumptions, it can be concluded that micro wind turbines would not be a financially beneficial investment for the University of Vermont. However, it is important to note that a simple financial analysis does not take into account external costs, such as impact on the environment. Reliance on wind energy would reduce that impact as it ultimately reduces our carbon footprint.

Nomenclature

P = Power (W)

C_p = Power Coefficient

ρ = Density (kg/m^3)

A = Cross-Sectional Area (m^2)

U = Wind Speed (m/s)

r = Blade Length (m)

Hz = Signal Frequency (Hz)

m = Transfer Function Slope

b = Transfer Function Offset

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1 Background & Objectives

Turbines can be an effective method of harvesting the energy from the wind and converting it into usable electricity. For all situations, such as the University of Vermont campus, there needs to be an analysis of viability before installation. The site viability includes a variety of factors relating to the actual location of the turbine.¹ Any installation of turbines begins with exploring financial viability to determine the Return on Investment (ROI). ROI is a ratio between net financial gains and investment cost, which is usually measured in years. A cost analysis would need to be run to determine energy saved and net cost or gain over a given timescale.² To determine if the installation would be profitable, an analysis of the wind conditions at a given sites to determine if the wind is consistent enough to generate power. If the location would generate significant power, the ease of installation/repairs need to be evaluated and the site needs to be tested to determine if it is structurally supportive of the installation. The proximity of humans needs to be considered as well in regard to noise generation or general human safety. An environmental impact needs to also be considered with how birds or other animals might be impacted from the turbines.³ These criteria would allow the university to determine if they should move forward with installing the turbine.

With the constant improvement of technology, turbines are becoming more viable as they can generate power at lower wind speeds and go longer without repairs.⁴ Unlike traditional turbines, micro wind turbines can benefit from being located closer to the electric user,

reducing losses due to wire resistance. Additionally, the small size of these units allows for placement in close proximity to large structures and relatively easy repairs and maintenance. For these reasons, the use of micro wind turbines is increasingly becoming a reality.⁵ For example, a site located at Hatiya Island in Bangladesh proved viable from having wind speeds above 6.0 m/s for more than 58% of the year.⁶

While micro wind turbines have some advantages over more traditional turbines, there are a few draw backs, one of which is reduced sweep area. Sweep area size directly relates to power generation. The formula for power generation by turbine is defined the expression as follows.

$$P = \frac{1}{2}C_p\rho AU^3 \quad (1)$$

For this equation, ρ is the density of the fluid, which is air for wind turbines. A is the sweep area of the turbine. U is the wind speed, specifically its movement perpendicular to face of the turbine. C_p is the coefficient of power, which is a ratio of the power extracted to the power available. The maximum value of C_p is .593, which is known as the Lanchester-Betz limit.⁷ When determining a viable source of energy, it is important to maximize all variables to harvest a large amount of energy. Due to the close proximity of other buildings, sweep size is limited, reducing the quantity of energy harvested. As seen by equation 2, the radius

squared influences the power generated.

$$A = \pi r^2 \tag{2}$$

While not as impactful as wind speed, small increases in the radius still produces large increases in power.

Additionally, buildings are an obstruction for wind flows. These buildings create a wake in the flow, ultimately reducing wind speed and causing turbulence. Turbulence, being unsteady movement in the fluid, also reduces the ability to harvest the energy.⁸ There are also fixed costs with any project that don't vary much with respect to the turbine size. For example, the installation cost for a 500W turbine could be about the same as a 1000W turbine. For ROI, the 500W turbine would take much longer to start being profitable. A combination of these factors have led most micro wind turbine projects to be unsuccessful. The buildings create a much larger boundary layer than alternative geographical locations such as a desert or ocean setting.⁹ Despite prior studies showing poor results from their tests, it is important to collect data from potential sites in order to confirm the hypothesis.

The University of Vermont is an urban location which could potentially benefit from wind energy. Many windy parts of campus could be utilized to generate power through micro wind turbines. By collecting wind speed data on campus, the annual energy harvested can be

estimated. This will provide insight into the viability of a micro wind turbine installation.¹⁰ A turbine could possibly save money through a reduced electrical bill, and hopefully the data shows that the cost of the turbine will be paid off by its power generated within a certain time span. Ultimately, the objective of this study is to explore the viability of installing micro wind turbines on the University of Vermont campus. The threshold value for viability will be set at 1% of the universities total electrical consumption.

2 Methods

2.1 Equipment

An anemometer was used to measure wind speed. For this experiment, an NRG Systems #40C anemometer was used as seen in figure 1.



Figure 1: An NRG Systems #40C anemometer.

The cups catch the wind and produce rotation. The greater the wind speed, the greater the rotation. When the cups are spinning, a frequency signal is generated. This signal is converted in to a wind speed as can be seen in equation 3.

$$U = m * Hz + b \quad (3)$$

The anemometer used was calibrated at NRG Systems with $m = 0.765$ and $b = 0.35$. This equation shows a linear relationship between frequency and wind speed. It should be noted that when the anemometer has no rotation, a frequency 0 Hz is produced. As a result, a wind speed of 0.35m/s is calculated. This is due to low wind speeds being difficult to detect by the NRG Systems #40C anemometer. For this reason, all wind speeds between 0m/s and

0.35m/s will be treated as negligible wind speed for power generation.

Accompanying the anemometer is an NRG Systems Symphonie Plus data logger as seen in figure 2.



Figure 2: An NRG Systems Symphonie Plus data logger.

The logger is connected to the anemometer by wire and receives the frequency signal. Programmed with the proper slope and offset, the logger applies the transfer function, equation 3, to measure a wind speed. Collecting multiple wind speed data points, the logger records the minimum, maximum, standard deviation, and the average speed for a ten-minute interval. This information is then time stamped and saved on an SD card. The logger con-

tinues to record the data at ten-minute intervals until the SD card is removed.

While the logger is waterproof when sealed, one last measure was used to protect the logger from weather. A weather protection box can be seen in figure 3.



Figure 3: An NRG Systems weather protection box.

The box was then elevated off the floor to allow draining in the case water penetrated the box. Ultimately, the protective equipment was effective and allowed for data collection with no issues due to weather.

2.2 Proposed Turbine Site

The first step in determining viability is selecting a potential site. The opening under the Central Campus Residence Hall bridge was selected as I observed it having relatively high winds. Due to the geometry of the building, wind across a large region gets funneled through a small opening. The building with the bridge can be seen in figure 4.



Figure 4: Opening under Central Campus Residence Hall.

As shown by equation 1, the power generated is the cube of the wind speed. Using a location with consistently high wind speeds allows to compensate for the small area downsides of micro wind turbines. A close up of the actual orifice can be seen in figure 5



Figure 5: Close up of tunnel.

This passage has a size of 10.67 meters across and 4.12 meters high. This region will be the theoretical installation point. When calculating power generated, a subset of this area will be used. Unfortunately, placing an anemometer at this specific location proved difficult due to uncertainties with mounting and its high foot traffic. As an alternative, another location was selected to collect the wind speed.

Due to the size constraints of the selected location, a suitable turbine was selected as a theoretical candidate. A 400-watt wind turbine, the ASWT-400W, from Atlantis Solar. This was ideal for the location as its sweep diameter was 1.25 meters. If installed hanging

from tunnel, the small diameter would allow for foot traffic underneath to continue unobstructed. Additionally, multiple turbines could be hung next to each other for additional power generation. Hanging three turbines would allow for increased power generation, while providing 5.63 m to space out the turbines. Figure 6 shows the turbine selected.¹¹



Figure 6: The Atlantis Solar 400-watt wind turbine.¹¹

2.3 Anemometer Test Site

The anemometer installation site selected was on the roof of Votey Hall. Installation was made easy by the already existing test site as seen in figure 7.

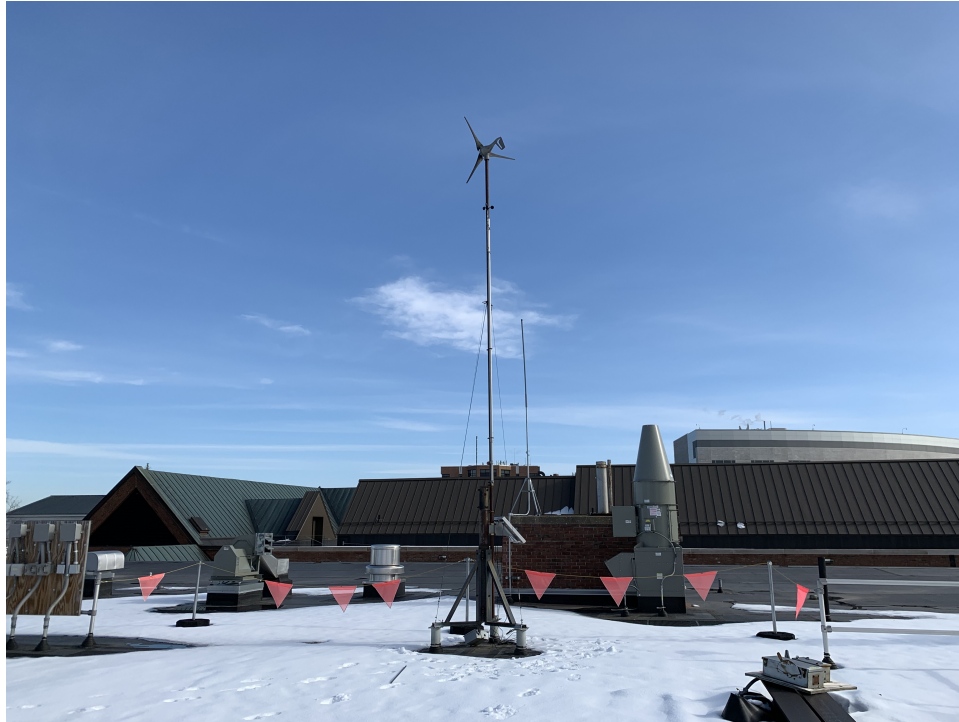


Figure 7: Anemometer installation site.

Prior wind related experiments utilized a turbine extending off the roof. The #40C anemometer used for my experiment was mounted to this rod roughly three meters off the ground. While ideally mounted further above the roof, this proved sufficient for data collection. Additionally, the anemometer was far enough below the already installed wind turbine to not fall in its wake. The final setup of the anemometer and logger can be seen in figure 8.



Figure 8: The final data collection setup.

The anemometer can be seen protruding off the rod at the top of the screen and the weather box with data logger inside are located near the base of the rod. While ideally, a full year's worth of wind speed is required to make accurate conclusions about a site, for this experiment only 19 days were recorded in March. Due to higher wind speeds in the

winter months, if the winter data showed relatively low wind speeds, it can be concluded that the annual average wind speed would be even lower, which would call into question whether installation of micro wind turbines on the University of Vermont campus would be viable. The Burlington, VT wind speeds can be seen in figure 9, where it reveals how my data collection time was during the windiest part of the year.¹²

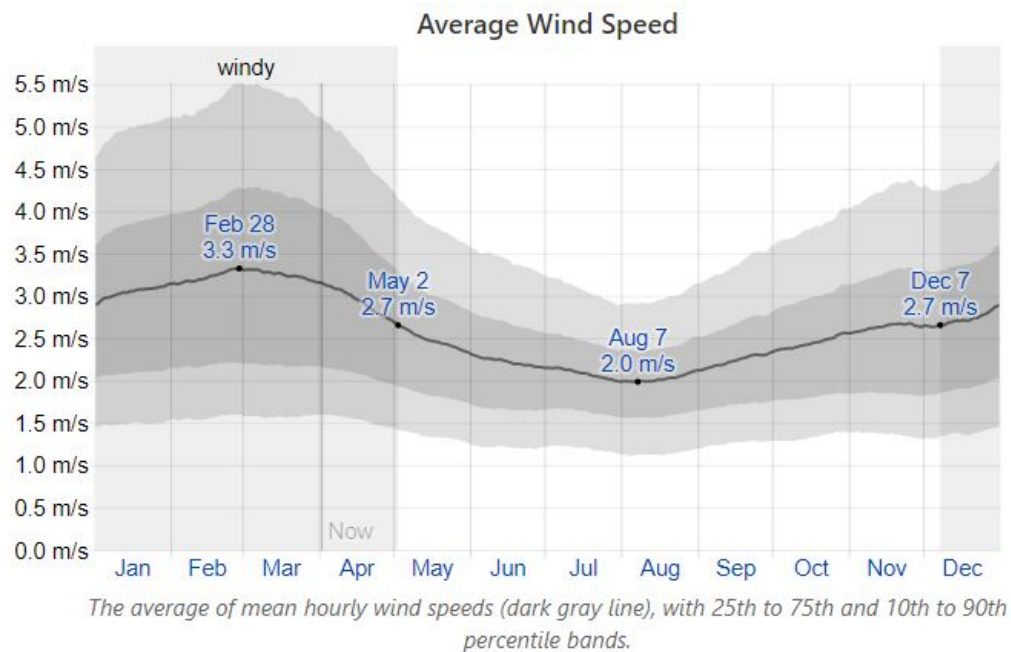


Figure 9: The average wind speeds in Burlington, VT over a year.¹²

Theoretical power will be generated using two separate methods. One method will be utilizing the fundamental wind power equation or equation 1. The other will use the power curve provided by Atlantis Solar for the 400w turbine selected. Figure 10 shows the power curve provided.¹¹

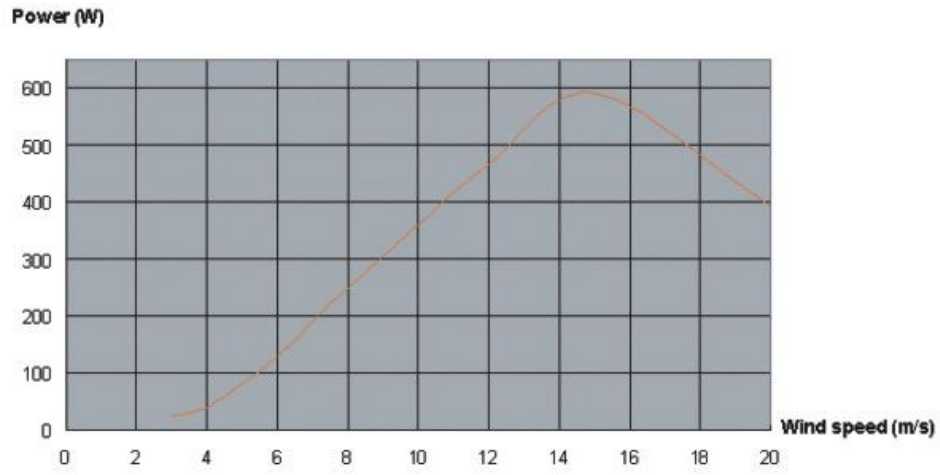


Figure 10: The Atlantis Solar 400 W wind turbine power curve.¹¹

3 Results

Over the 19 days of data collection, a total of 2599 wind speed averages over ten-minute intervals were collected. There were a total of 433.17 hours recorded in the data. The wind speed averages over this time span were plotted as seen in figure 11.

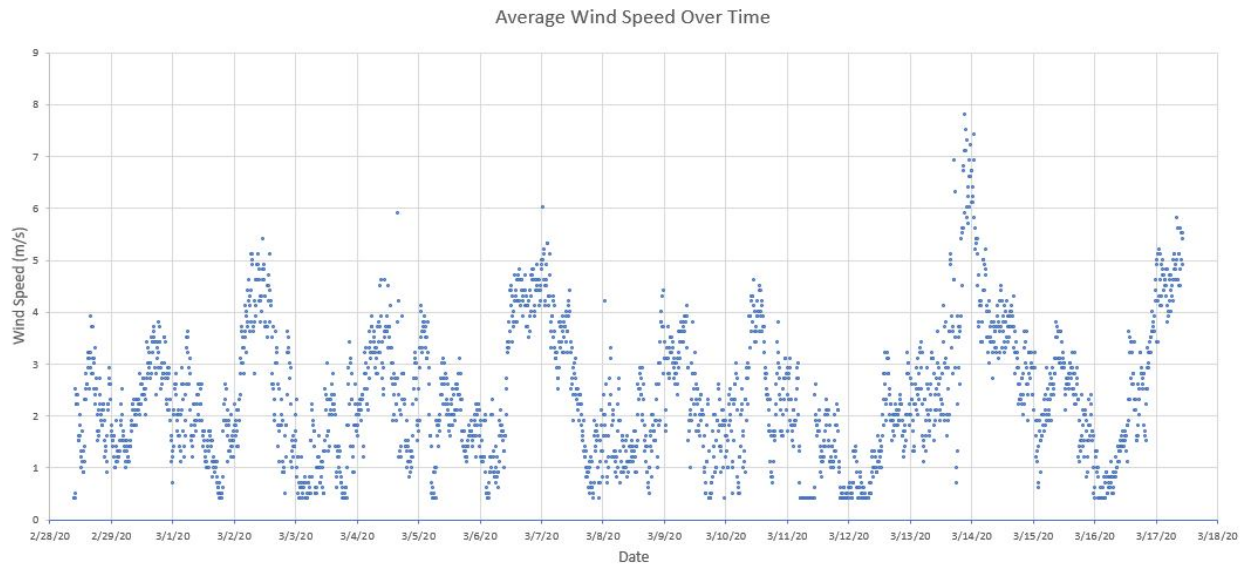


Figure 11: Average wind speed over time.

This data was then broken into a wind speed frequency plot to show how frequent various wind speeds were recorded. This plot can be seen in figure 12.

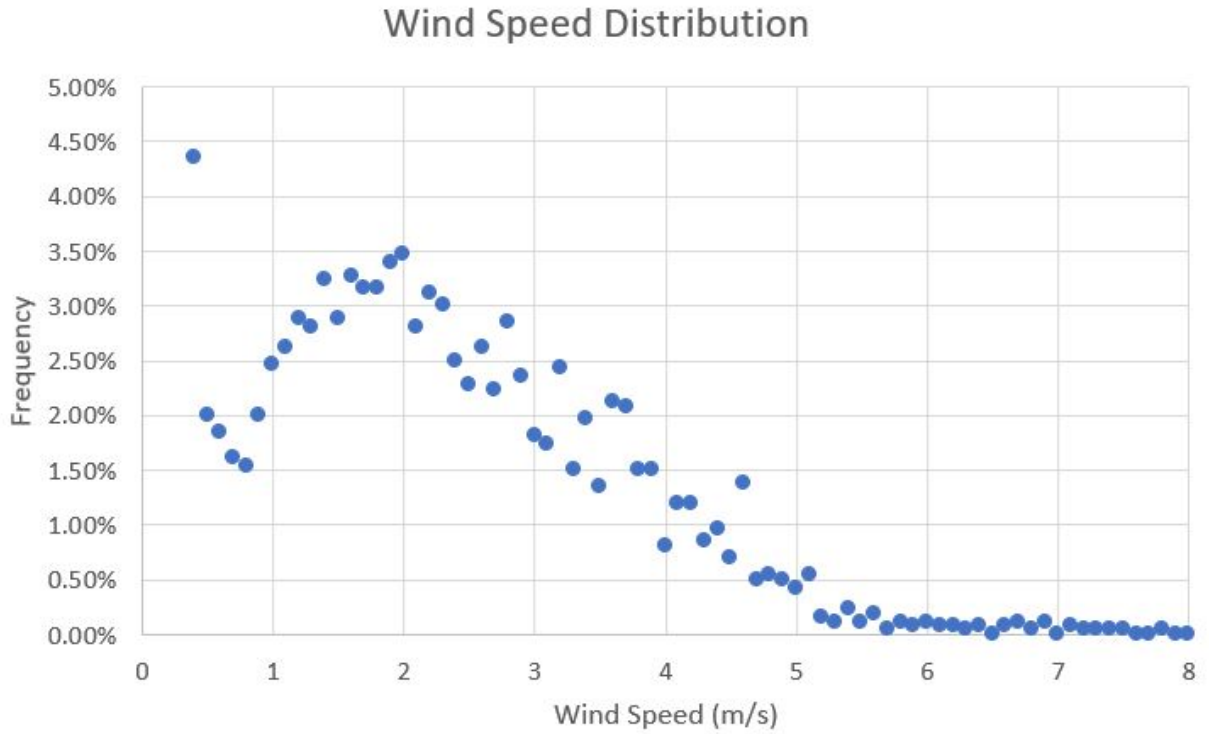


Figure 12: The frequency of any wind speed.

The point at a wind speed of 0.4 m/s has a much higher frequency than all other wind speeds on the plot. This is because 0.4 m/s is the minimum value which can be recorded, meaning all average wind speeds between 0 and 0.4 m/s all get recorded as 0.4 m/s. Fortunately, this doesn't impact our results as none of these wind speeds could have provided power. Using the power curve provided in figure 10, an average power was calculated. The startup wind for the 400 W turbine is 2.5 m/s and the minimum working wind speed is 3 m/s. Of the 2599 data points, only 769 showed a wind speed of 3 m/s or greater. Using this

power curve, the average power generated above 3 m/s would be 47.58 W.

Using the the fundamental power generation equation, equation 1, another power curve was created. For this equation, C_p was 0.4, the sweep diameter is 1.25 m, and the density of air is 1.225 kg/m^3 at STP (Standard Temperature and Pressure). While density varies with temperature, the temperature changes for the test location would only slightly change the density, producing a small impact on power generated. The region of possible power generation, between 3 and 8 m/s wind speed was then plotted as can be seen in figure 13.

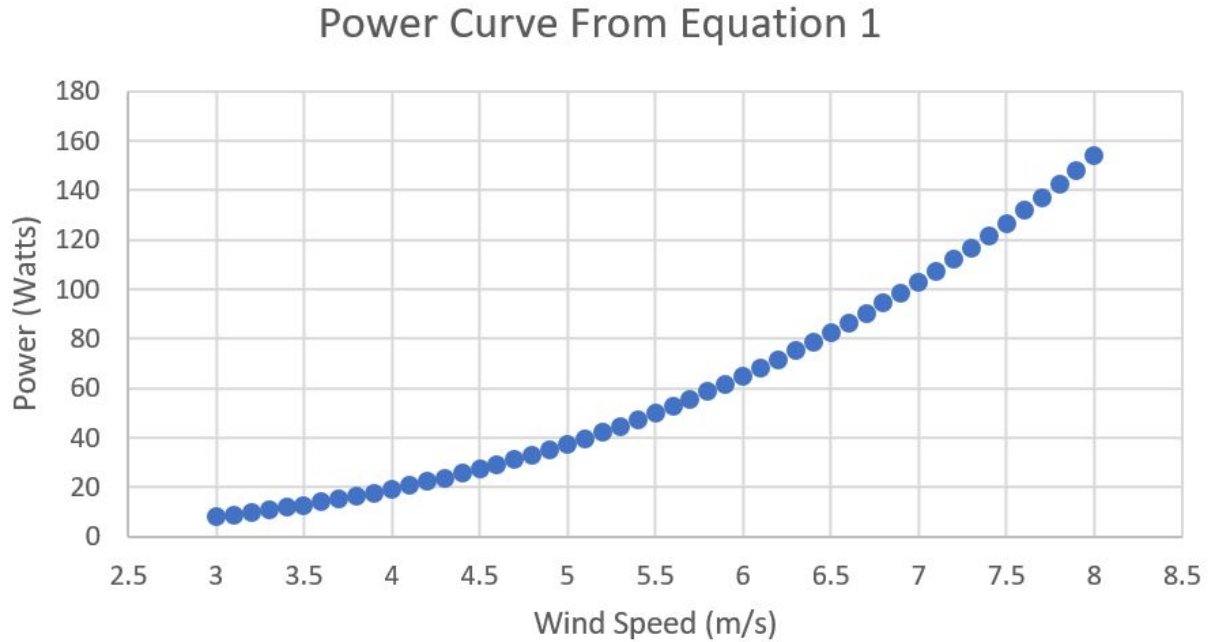


Figure 13: The power curve from equation 1.

Using the data collected along with the power curve in figure 13, the average power

generated for the Atlantis Solar 400 W wind turbine for a wind speed greater than 3 m/s is 21.19 W.

4 Discussion

The wind speed required to start generating power is 3 m/s. This means that if a turbine was installed instead of an anemometer, it would only generate power for 29.59% of the time. While this study captured data from only a small subset of the year, it took measurements during the winter months, when the highest average wind speeds tend to occur. Thus, if a larger set of data was collected for the entire year, it would likely be lower than 29.59%. This value is significantly lower than most turbines require to justify their installation.

Additionally, the two average powers calculated of 47.58 watts for the given power curve and 21.19 watts for the calculated power curve are both very low values for power generation. The discrepancy between these two values has an unknown origin. A potential reason could be Atlantis Solar using a different method of generating the curve, such as physical measurements. Additionally, the blade diameter provided on the website could be incorrect changing power generated using the power equation. Regardless, the results for each approach tend to show a relatively low power generation. For purposes of the study, the Atlantis Solar power curve will be used as it most likely came from experimental measurements. This is

the higher power curve and will provide an optimistic approach for the cost analysis.

For the Atlantis Solar power curve, it deviates from the expected cubic trajectory predicted by equation 1. While it begins to steepen near the beginning, it appears linear as wind speed increases. This can be attributed to C_p , the power coefficient. C_p is a function of the rotor tip-speed ratio and pitch angle. For most turbines, pitch angle is a constant making the tip-speed ratio the only factor for influencing C_p . The tip-speed ratio is a relation between the speed of the tip of the rotor and the wind speed. As wind speed increases, C_p initially increases to a maximum before dropping at higher wind speeds. The tip-speed ratio is important as too fast rotation of the rotors could exceed the structural integrity of the turbine. The decrease in C_p occurs at a similar wind speed to the rapid rise in power. This decrease in C_p results a linear trend where a cubic trend is expected.¹³

In Vermont, the commercial electricity rate is \$0.141/kWh.¹⁴ Using the optimistic power generation rate, the turbine would generate 123.34 kWh every year. This means the turbine would save \$17.36 annually. With an estimated acquisition cost of \$400, the turbine would take a minimum 23 years to pay itself off in savings, without factoring in the maintenance expense associated with a turbine exposed to weather for an extended period of time.¹⁵ In comparison, the average American home consumed 10,972 kWh.¹⁶ This means that the power generated from the optimistic model would only cover for 1.12% of the average American home's energy expenditure. If three turbines were installed as proposed earlier, it would

only increase the energy coverage to 3.37%. For the alternative power curve, this value and resulting savings would be even lower at an energy coverage of 0.50% for one turbine and 1.50% for three turbines.

In comparison to the average American home, the University of Vermont consumed 47,723,274.60 kWh in 2019. The university spends more than 4350 times the amount of energy as an average American home. One turbine installed with the optimistic power curve approach would account for 0.000259% of the university's energy consumed in 2019. To meet our threshold value of 1% of the university's energy usage, there would need to be at least 3,870 turbines installed.¹⁷

5 Alternative Solution

Other wind turbines on the market could prove to be more viable. A 2.1 MW wind turbine, the AGW 110/2.1, made by WEG Industries was selected. A photo of the 2.1 MW turbine can be seen in figure 14.



Figure 14: A WEG Industries AGW 110/2.1 Turbine.¹⁸

The diameter of this turbine is 110 m. It would not fit in the selected location under Central Campus Residence Hall, but it could provide much more power than the smaller turbine selected. The 2.1 MW turbine's power curve can be seen in figure 15.¹⁹

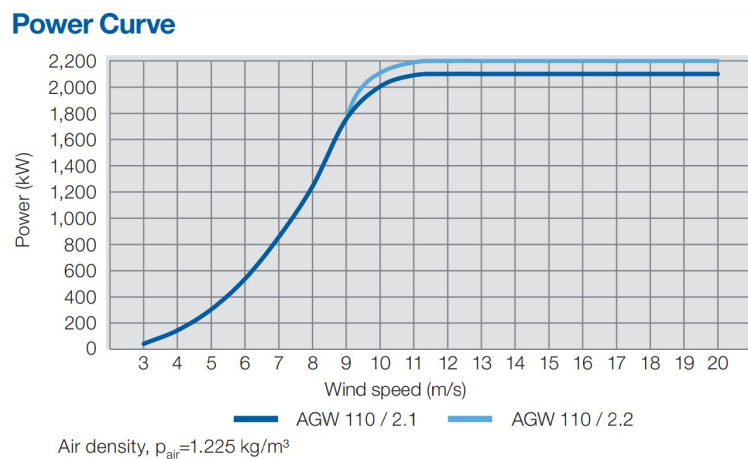


Figure 15: The power curve for the AGW 110/2.1 Turbine.¹⁹

If the wind speeds collected are applied to this power curve, the power generated is significantly higher than that generated by the micro wind turbine. For the 29.5% of the time which the turbine would actually be generating power, it would produce 166.5 kW. This means the annual energy production would be 431,677 kWh. If just one of these turbines were installed, and were subject to the wind speed data that was collected, it would produce enough power to cover the energy expenditure of 39 average American homes. For UVM, it would account for 0.905% of the university's energy usage in 2019. This came much closer to the threshold that was set and would significantly reduce less renewable sources of power production.

This alternative would provide much more energy for UVM, but would come at a greater cost of millions of dollars to purchase, install, and maintain.²⁰ Additional, this massive turbine could not be installed on the UVM campus and would need an alternative location. Fortunately, the average wind speed in the Burlington area is higher than that collected from the Votey Hall anemometer. This means it would have an even higher power output than calculated. While this could be a potential alternative, an entire study would need to be performed to support the viability and positive impacts of a large scale turbine.

6 Conclusion

While wind energy is more environmentally friendly than traditional electric generation methods, the micro wind turbine approach is not financially viable for the University of Vermont. This experiment stuck to generous conditions and made assumptions in favor of wind energy, but still fell short due to a 23 year pay off period. Within the 23-year time span, additional cost for maintenance and general wear would only increase the total cost. Despite the high financial cost, there are potential solutions to incentivize renewable energy harvesting. Government provided subsidies could reduce the pay off period, making the switch to wind energy more feasible. If external financial support was provided, the three turbines would still barely dent the University of Vermont energy expenditure. Of course, this analysis does not take into account external costs of reliance on fossil fuels, such as impact on the environment. For this reason, the university should still try to find viable energy alternatives to try and reduce its carbon footprint, such as large turbine wind energy.

The results of the experiment were expectantly negative. Conducting the experiment was still a rewarding experience. Throughout the process, I learned many things regarding wind energy and data collection. The data collection process was full of unseen hurdles which challenged me to find new and creative solutions to problems. These solutions often included generalizations or simplifications to the experiment, but provided me with insight on how to approach similar problems in the future. For this study, I would want to gather data from

more locations on campus, specifically the exact location for the proposed turbines. This would give a better idea of viability rather than a regional approximation. Additionally, I would want to explore alternative locations for larger scale turbines which could provide a greater source of power. Lastly, I think that wind energy should be used in parallel with other forms of renewable energy, such as solar or hydro. These alternative types of renewable energy could be viable solutions for the University of Vermont. Ultimately, this project was a success for the educational benefits despite proving micro wind turbines not viable in the tested location for the University of Vermont.

7 Acknowledgements

I would like to thank my primary advisor, Dustin Rand, for the support and insight he has provided me throughout the project. Being my main source of advice throughout the thesis allowed for the project to succeed. I have learned a lot from his expertise in wind energy and experimental methods which will stick with me for future projects to come. Dr. Linda Schadler, Dean of the College of Engineering and Mathematical Sciences, inspired me to pursue the topic and encouraged me to continue work in difficult times. Douglas Dickey, Assistant Dean, helped me get the proper approval to utilize the roof space on Votey Hall for testing. Dr. Chris Danforth, UVM Professor, supplied interest, support, and agreed to be on

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